Exoplanets with WFIRST: Science Questions, Goals, and a FOM

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With input from David Bennett and the ExoSubCommitee

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2011 Sagan Exoplanet Summer Workshop

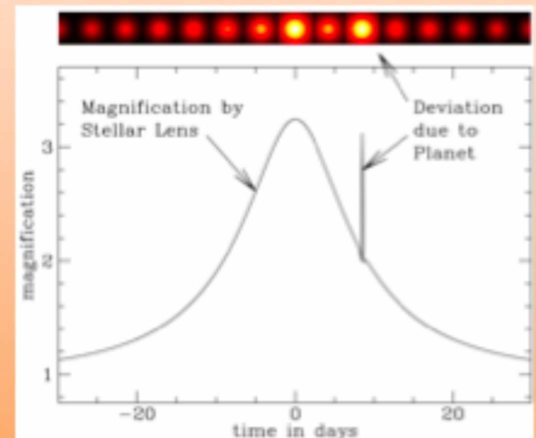
Exploring Exoplanets with Microlensing

July 25-29, 2011, California Institute of Technology

June 7, 2011: Early Registration Fee deadline

Topics include:

- History of Microlensing, Theory, Detection and Follow-up
- Introduction to Microlensing Photometric Techniques
- HST/AO Data Reduction
- Microlensing with Space-based Telescopes
- Modeling of Microlensing Data
- Extracting the Physical Parameters of Planetary Events
- Null Results and Detection Efficiency
- Future Prospects and Challenges of Microlensing



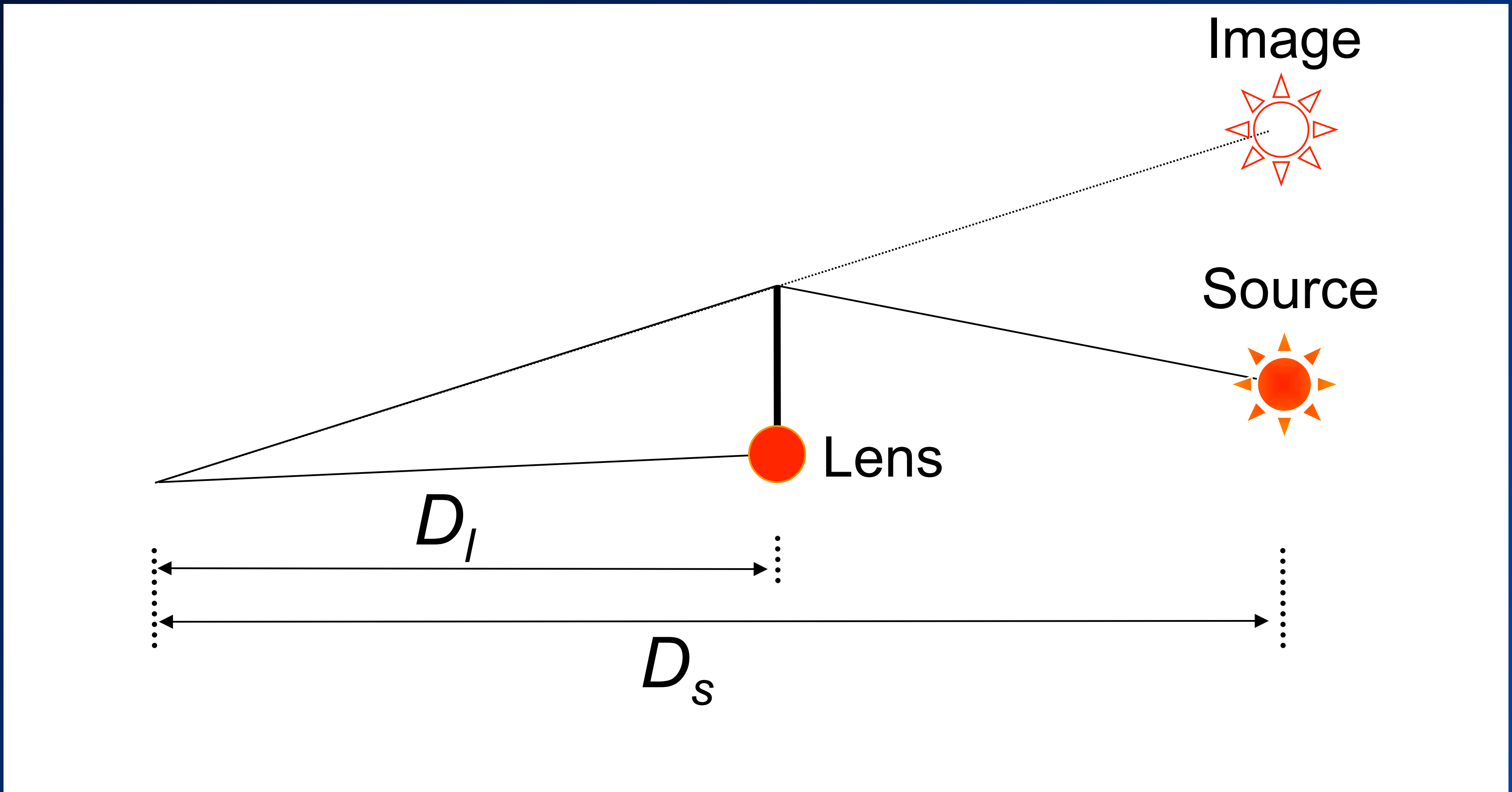
Hands-on Sessions during the week will allow attendees to work with microlensing data.

Scientific Organizing Committee

Dave Bennett (University of Notre Dame)
Ian Bond (Massey University, New Zealand)
Subo Dong (Institute for Advanced Study)
Scott Gaudi (Ohio State University)
Stephen Kane (NExScI)
Rachel Street (LCOGT)
Takahiro Sumi (Nagoya University)

http://nexsci.caltech.edu/workshop/2011

Microlensing Basics.



Einstein Ring and Images.

$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_{OL}D_{OS}}} \sim 700\mu\text{as}\left(\frac{M}{0.5M_\odot}\right)^{1/2}$$

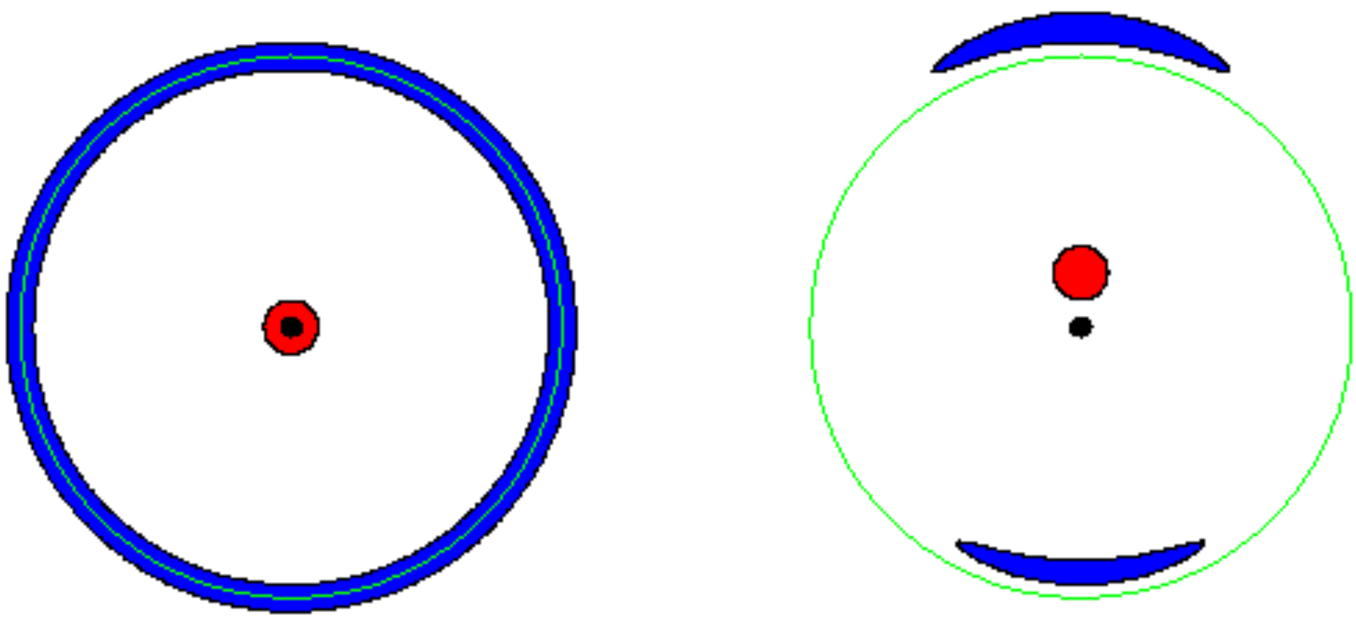
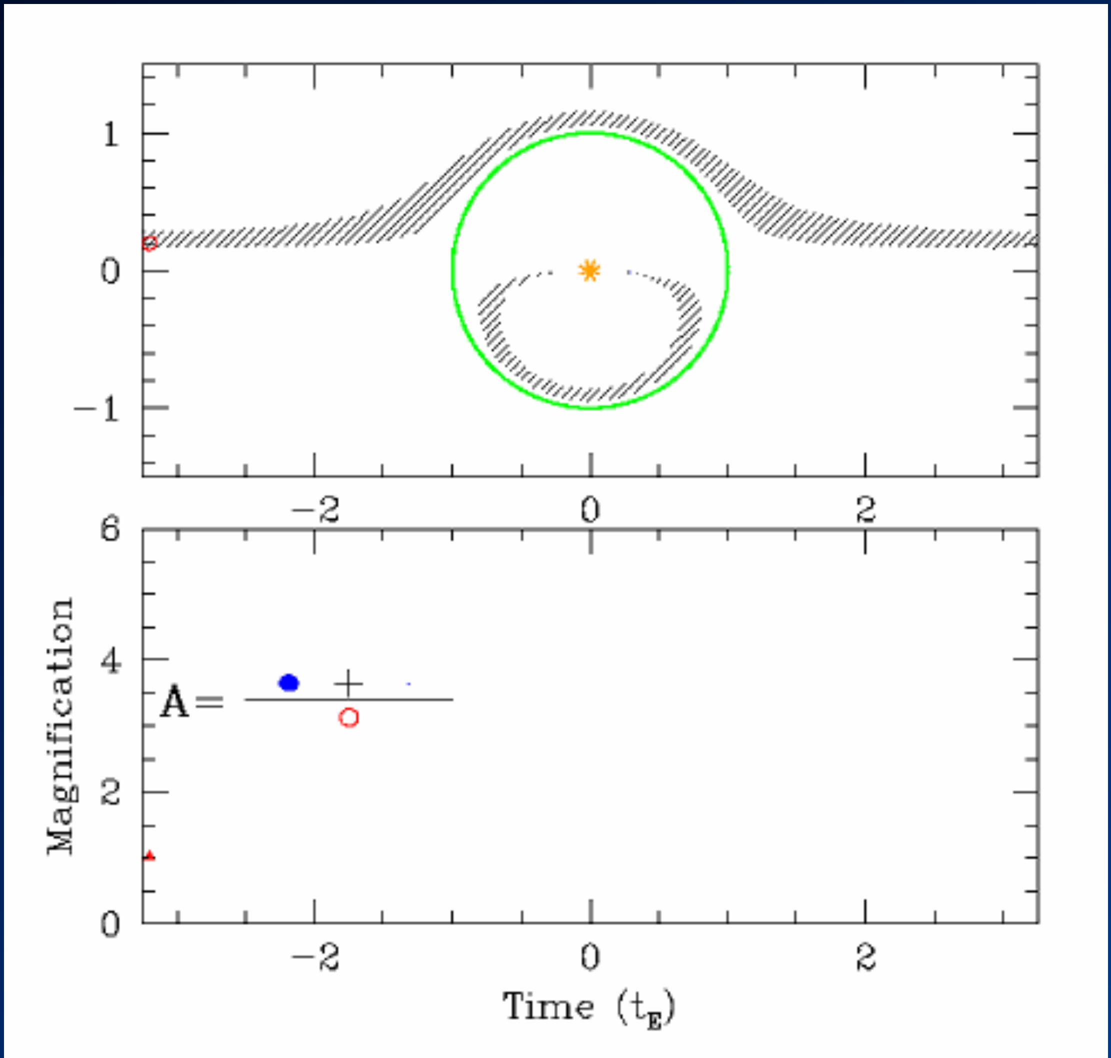


Image Separation $\approx 2\theta_E$

Magnification $= \dfrac{\text{Area of Image}}{\text{Area of Source}}$

Microlensing Events.



$$t_E = \frac{\theta_E}{\mu} \approx 25 \text{ days} \left(\frac{M}{0.5 M_\odot}\right)^{1/2}$$

$\mu \sim 1-15$ mas/year, $\theta_E \sim 0.1-2$ mas

- timescales of a few to hundreds of days
- ***stochasticity***
- degenerate function of the mass, distance to lens and source, and the relative lens-source proper motion.

Microlensing Event Rates.

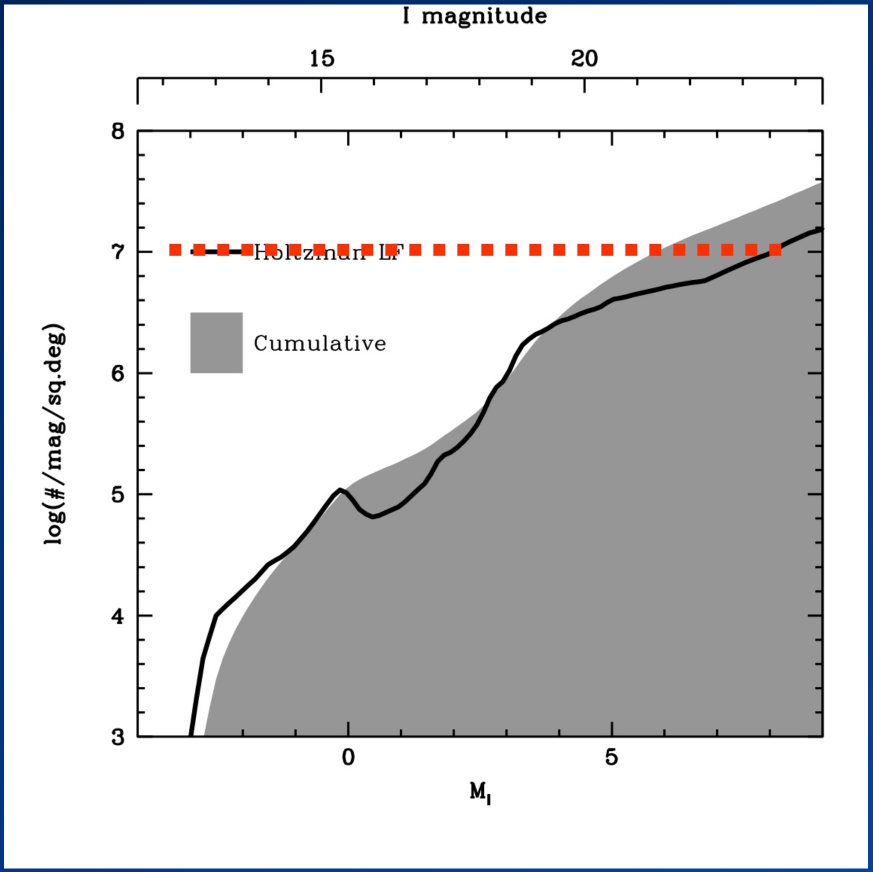
- Require a close alignment of ~1 mas.
- The event rate depends on the density distribution of masses along the line of sight.
- Event rate highest for stars in Galactic bulge.

$$\Gamma \approx 10^{-5}\ \mathrm{yr}^{-1}$$

- Total number of events depends on the luminosity function of bulge sources.

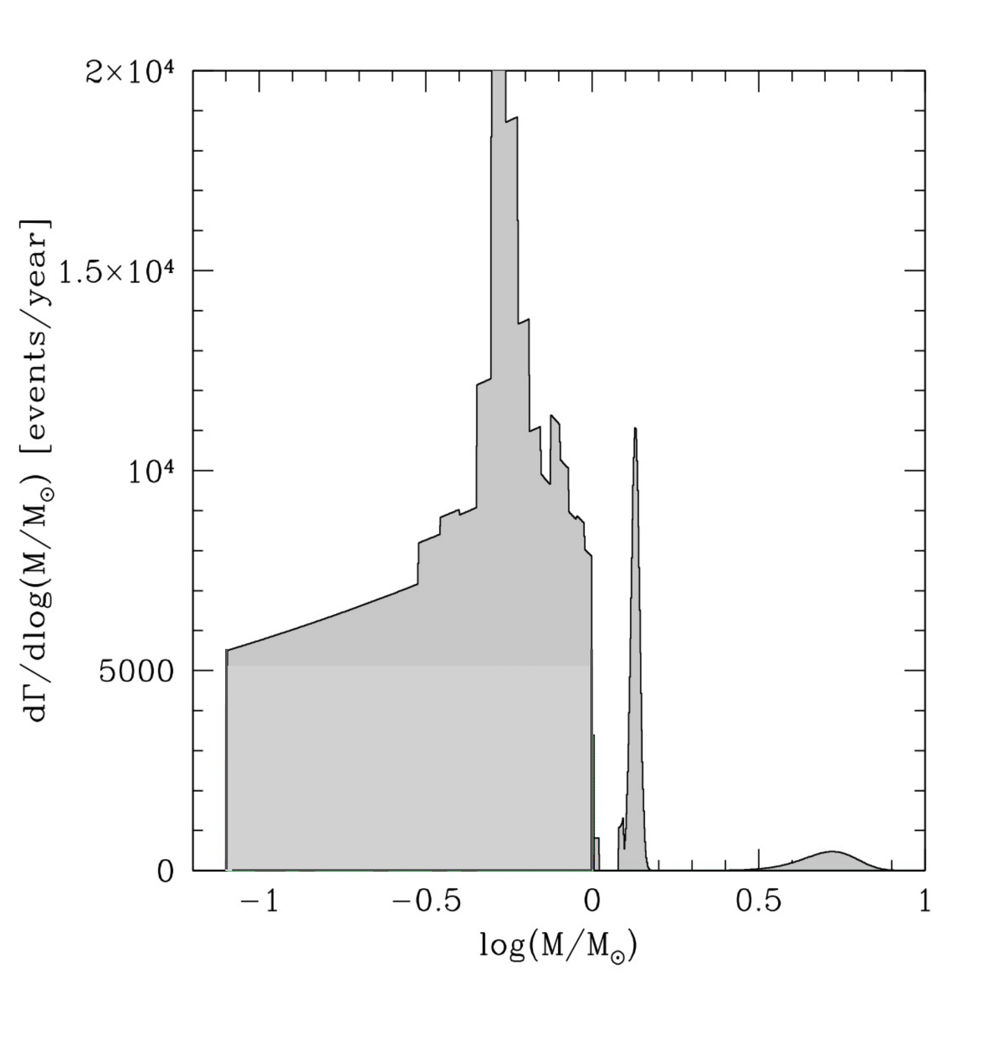
Bulge Luminosity Function.

- Fainter → more sources
- Fainter → smaller sources
- Fainter ⇔ FOV
- Longer wavelength → smaller sources, more extincted regions, higher event rates.



(mean separation ~0.5" for *I*<25)

Microlens Mass Spectrum.



Slight preference for higher mass lenses due to their larger Einstein ring radii.

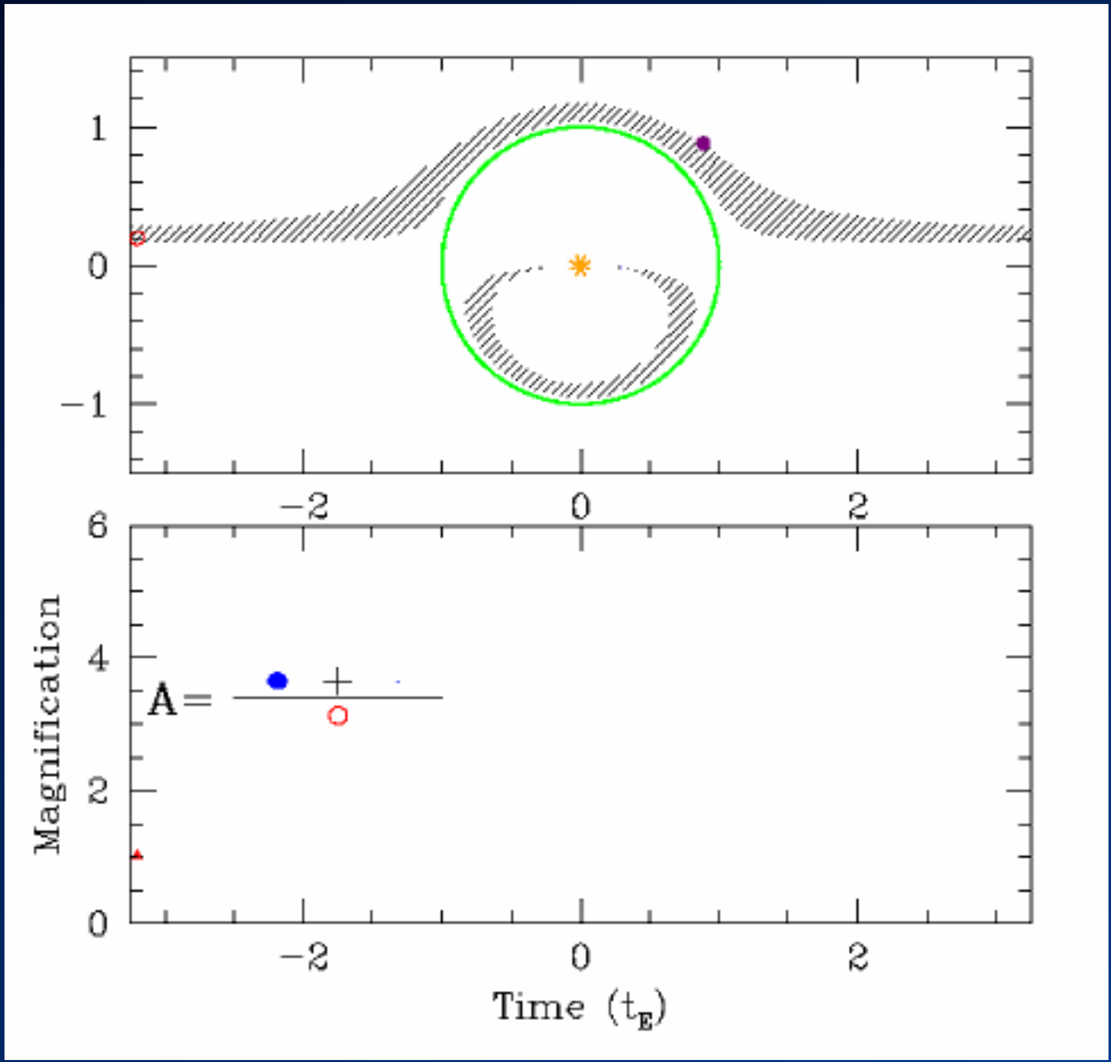
$\Rightarrow$ Most sources are at turn-off or just below.

$\Rightarrow$ Most lenses are $<M_\odot$,

$\Rightarrow$ Most lenses are fainter than (and blended with) the sources.

$\Rightarrow$ Lenses distributed along the line of sight (distances of 1-8 kpc)

Detecting Planets.



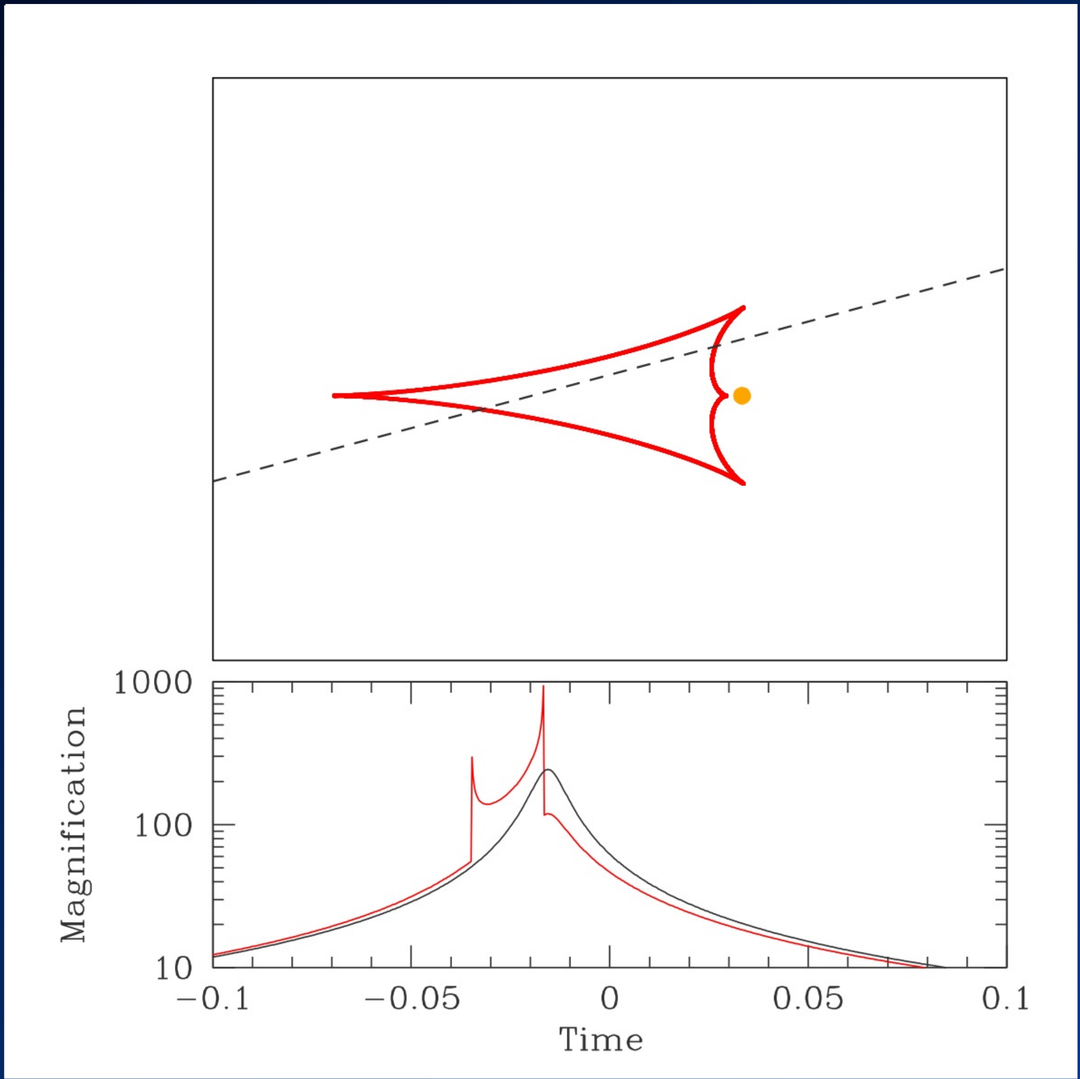
$$t_p = q^{1/2} t_E \approx 1 \text{ day} \left(\frac{M_p}{M_J}\right)^{1/2}$$

- Probabilistic
  - Must quantify the detection efficiency to infer frequencies.
  - Well-developed and well understood.
- High-Magnification means

  High Efficiency
- Maximized when

$$a \sim r_E = \theta_E D_l \sim 2.5\,\text{AU} \left(\frac{M}{0.5 M_\odot}\right)^{1/2}$$

High Magnification Events



Why high-mag events rule:

Nearly 100% efficiency.

(Griest & Safizadeh 1998)

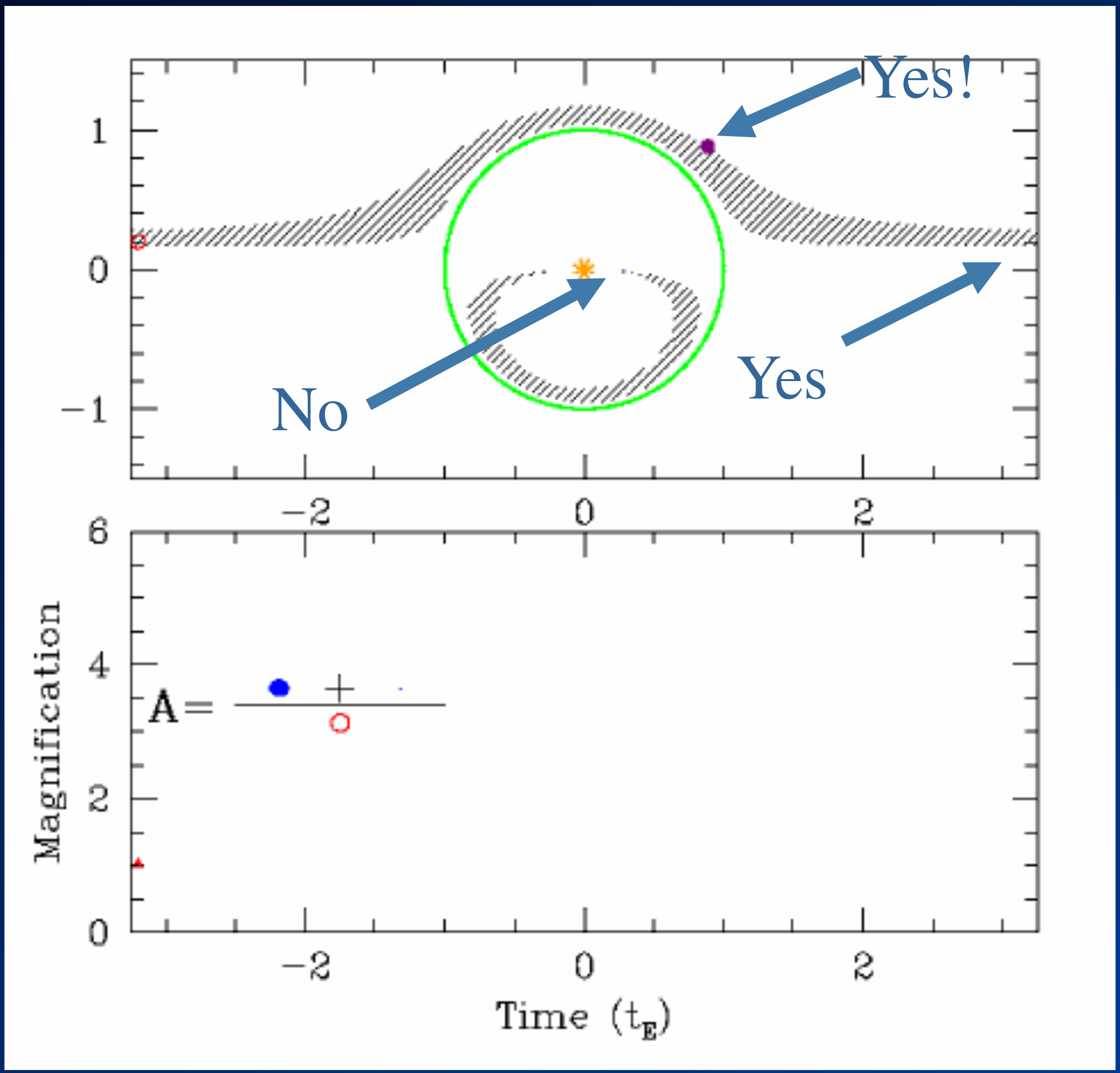
Localized perturbations.

Predictable.

Sensitive to multiple planets systems.

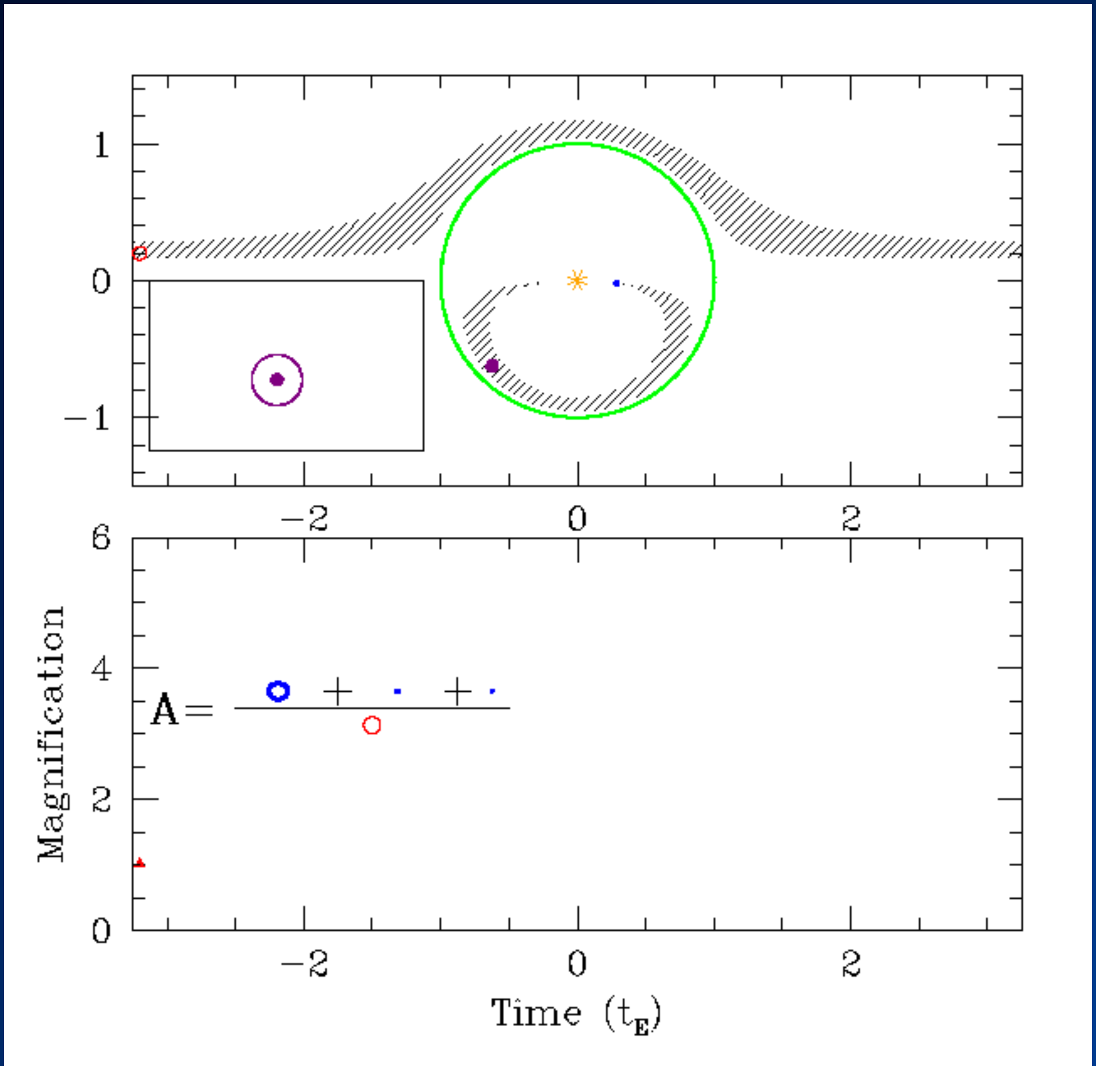
However, low-mag events are more plentiful, and the overall rate of perturbations is dominated by low-mag, unpredictable perturbations.

Perturbations: separation dependence



- Works by perturbing images
- Sensitive to wide or **free-floating** planets
- Not sensitive to very close planets (signal size is limited, perturbing demagnified images, blended with brighter image).

Perturbations: separation dependence



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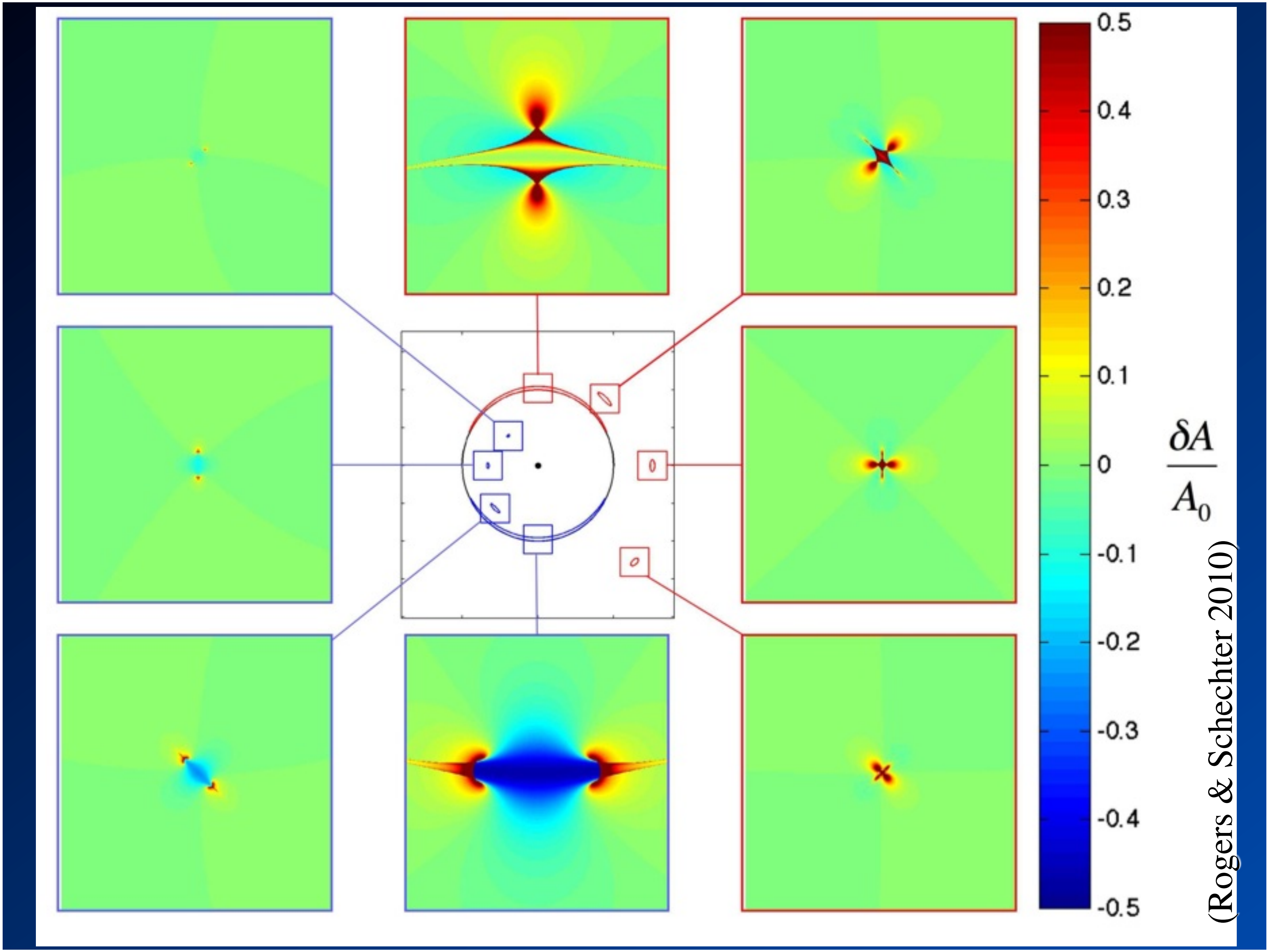
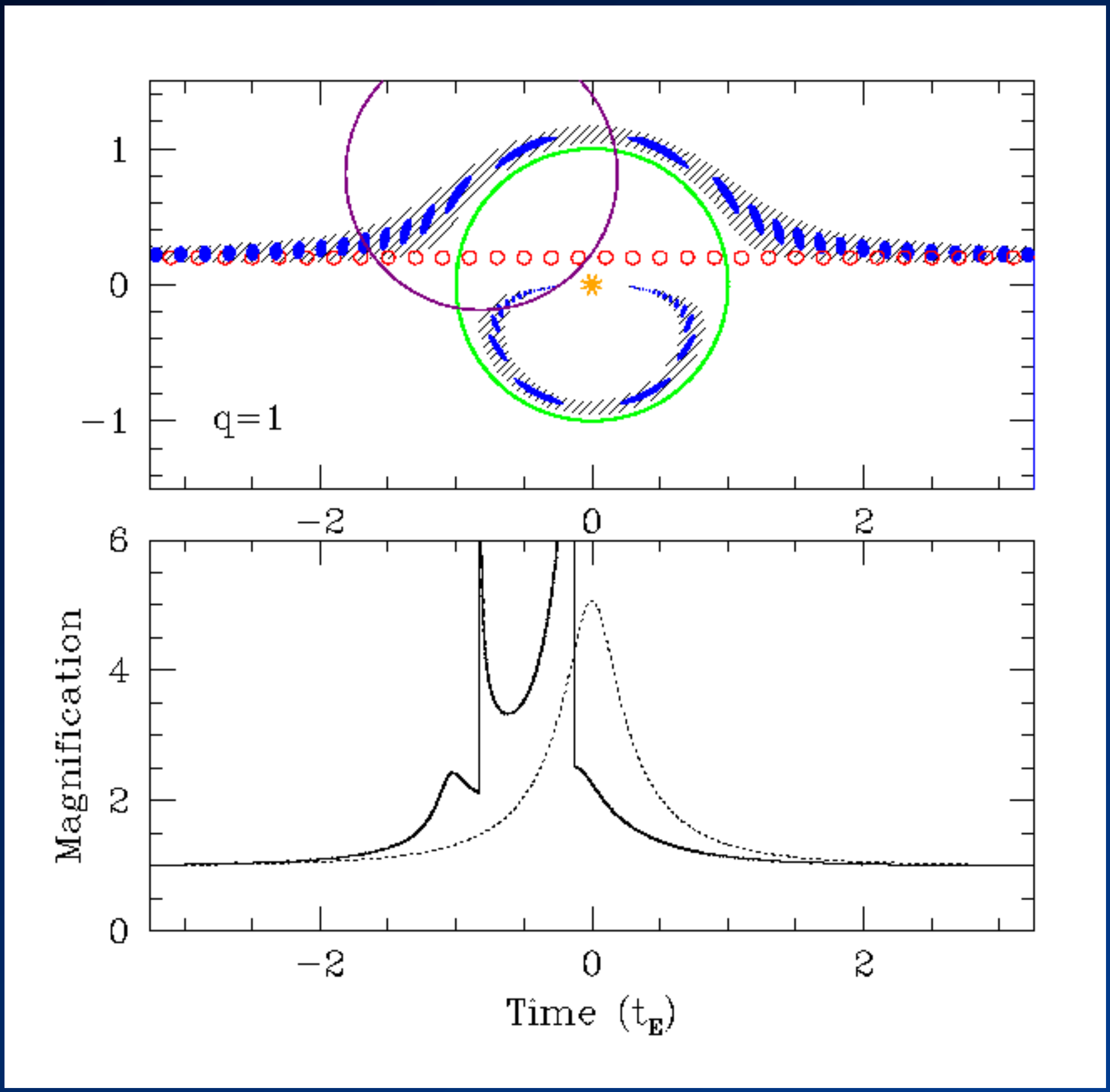


0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
$\frac{\delta A}{A_0}$
(Rogers & Schechter 2010)

Perturbations: mass ratio dependence

Signal magnitude is *independent* of planet mass ratio.



- Magnitude depends on separation of planet from image.
- Duration depends on mass ratio.

$$t_p = q^{1/2} t_E \approx 2\ \text{hrs} \left(\frac{q}{10^{-5}}\right)^{1/2}$$

- Detection probability depends on mass ratio.

$$P \sim A_0 \theta_p \sim \text{few}\ \% \left(\frac{q}{10^{-5}}\right)^{\sim 0.5}$$

Requirements.

- Event Rate
  - Primary Event Rate

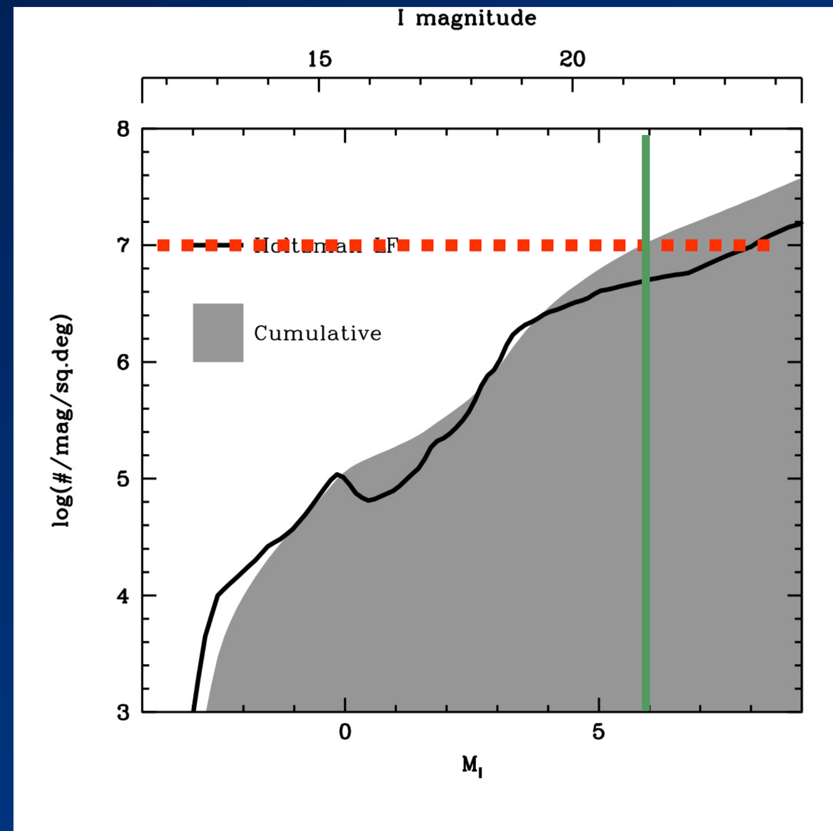
$$\Gamma \approx 10^{-5}\ \mathrm{yr}^{-1}$$

  - Detection Probability

$$P \approx A_0 \theta_p \approx 1\% \left(\frac{M_{Earth}}{M_p}\right)^{1/2}$$

  - Detections Per Year

$$N \approx N_E \Omega \Phi \Gamma P \approx 10\ \mathrm{yr}^{-1} \left(\frac{10\square^\circ}{\Omega}\right)\left(\frac{10^7/\square^\circ}{\Phi}\right)\left(\frac{10^{-5}\ \mathrm{yr}^{-1}}{\Gamma}\right)\left(\frac{1\%}{P}\right)$$



Requirements Part 2.

Detecting the Perturbations from Earth-mass Planets

- Sampling rate ~ 10 minutes

$$t_{E,p} = 2\,\mathrm{hrs}\left(\frac{M_p}{M_E}\right)^{1/2}$$

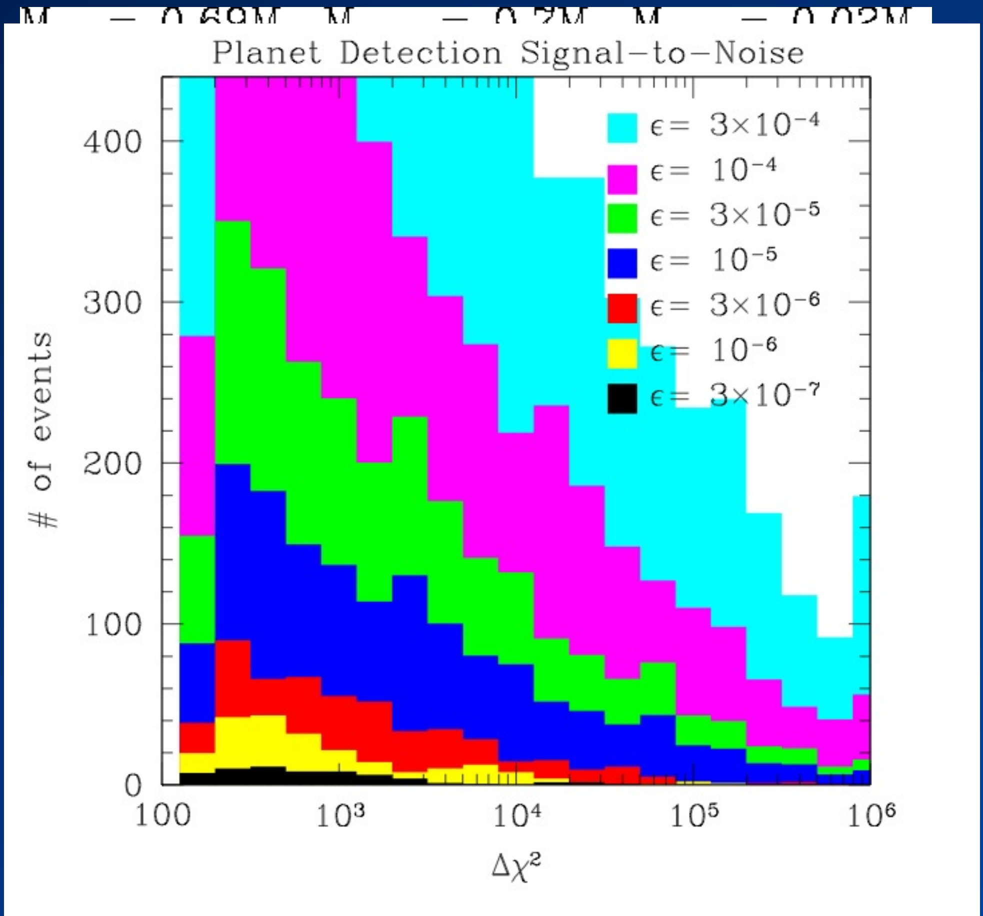
- Photometric Accuracy ~ 1% at I~21

$$\frac{\Delta F}{F} \approx 1\%\left(\frac{M_p}{M_{\text{♂}}}\right)\left(\frac{R_*}{R_\odot}\right)^{-2}$$

$$Q = 1\%\left(\frac{D}{2\mathrm{m}}\right)^{-1}\left(\frac{t_{\mathrm{exp}}}{120\mathrm{s}}\right)^{-1/2} 10^{0.2(I-21)}$$

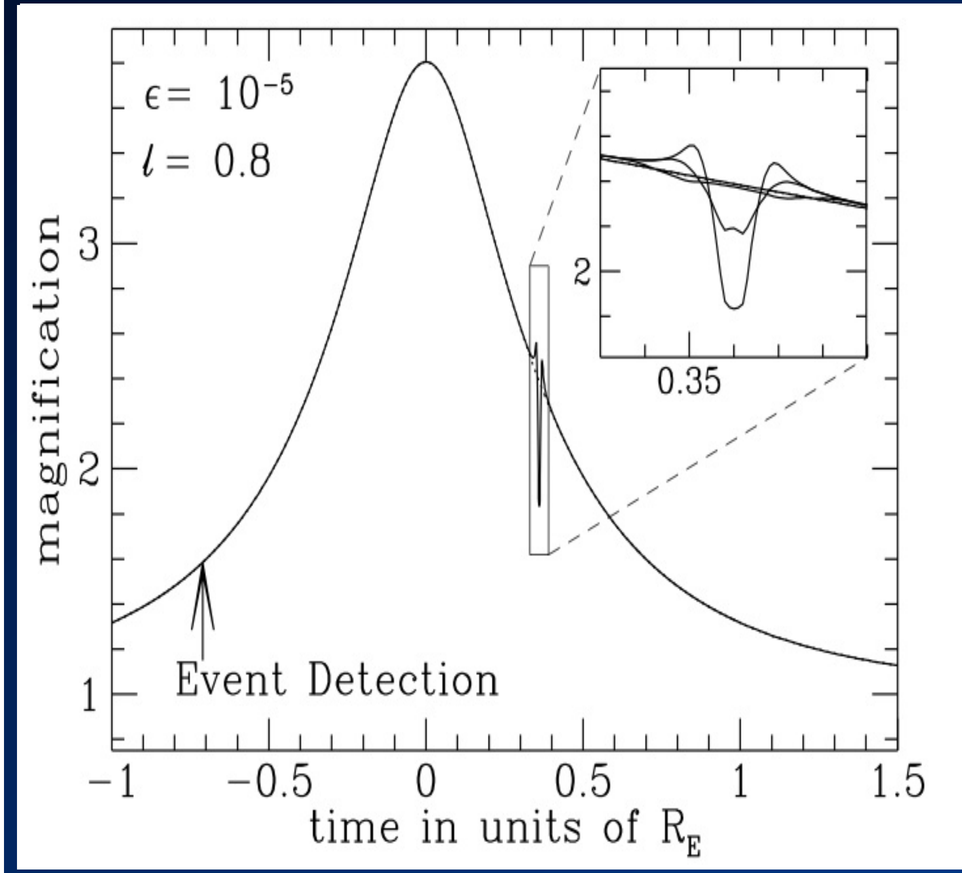
Perturbations: Characteristics

- Large and distinctive.
  - Essentially no astrophysical false positives.
  - Do not require extremely precise photometry in general.
    - Do no need to to worry about stellar variability, systematics.
- Shallow distribution of $\Delta\chi^2$
  - $dN/d\Delta\chi^2 \propto (\Delta\chi^2)^{-1.3}$ (index -2 to -3 for RV and transits)
  - Relatively gentle degradation.
- Not operating at S/N threshold
  - Do not need to worry about statistical false postiives.
- Perturbation parameters:
  - Duration $\Rightarrow$ Mass Ratio
  - Time of Perturbation $\Rightarrow$ Projected separation in θ_E



(Bennett & Rhie 2002)

Limits: lower mass limit



(Bennett & Rhie 1996)

$$\theta_E \approx \mu\text{as}\left(\frac{M_p}{M_\oplus}\right)^{1/2} \longleftrightarrow \theta_* \approx \mu\text{as}\left(\frac{R_*}{R_\odot}\right)$$

$$\rho_* = \frac{\theta_*}{\theta_E} \approx 1$$

- When $\rho_* >> 1$, top-hat perturbations, with height ρ_*^{-2} and duration $2\theta_*\mu^{-1}$ ~ few hours for major image perturbations.
- For minor image perturbations no excess magnification.

Limits: Lower Mass Limit

- The finite size of the sources sets the ultimate lower mass limit for detection.
- The source crossing time sets the required cadence of ~10 minutes.
- Small sources allow the detection of smaller planets
  - Late type stars - fainter, IR.
- Source size more important for closer planets.

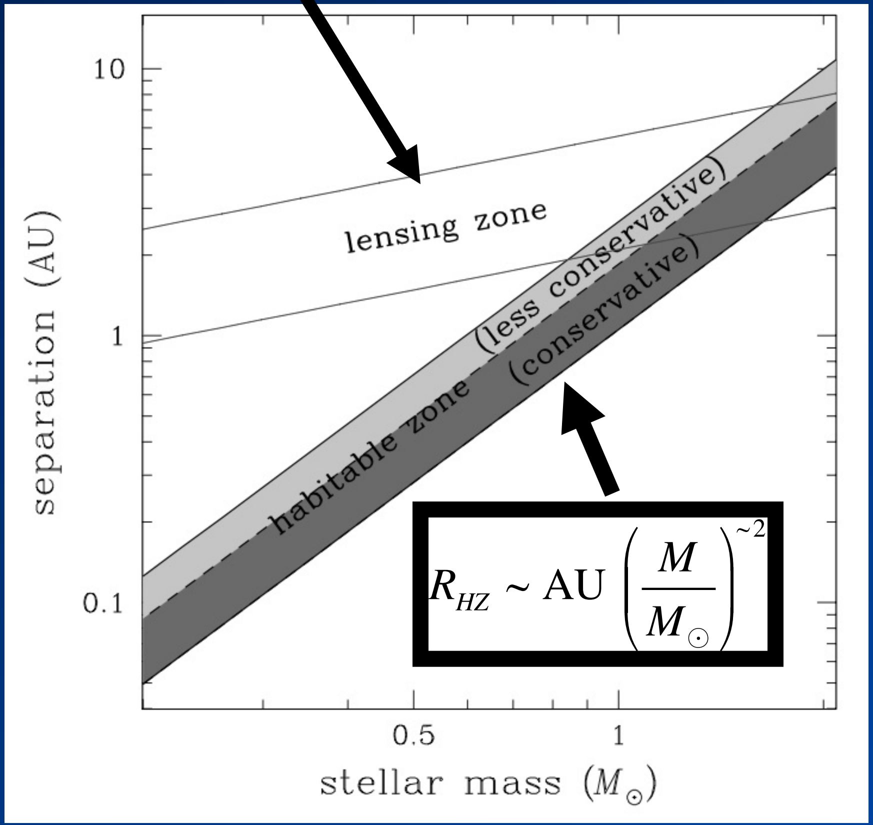
Limits: Habitable Planets.

$$R_E = \theta_E D_l \sim 3.5\,\mathrm{AU}\left(\frac{M}{M_\odot}\right)^{1/2} [x(1-x)]^{1/2}, \quad x \equiv \frac{D_{ol}}{D_{os}}$$

- Habitable zone is well interior to the Einstein ring radius for most lenses.

$$\frac{R_{HZ}}{R_E} \sim 0.3 \left(\frac{M}{M_\odot}\right)^{\sim 3/2} [x(1-x)]^{1/2}$$

- Minor image perturbations.
- More sensitive to source size.
- Require better precision.
- Can be made up by more time through the "x" factor.



$$R_{HZ} \sim \mathrm{AU}\left(\frac{M}{M_\odot}\right)^{\sim 2}$$

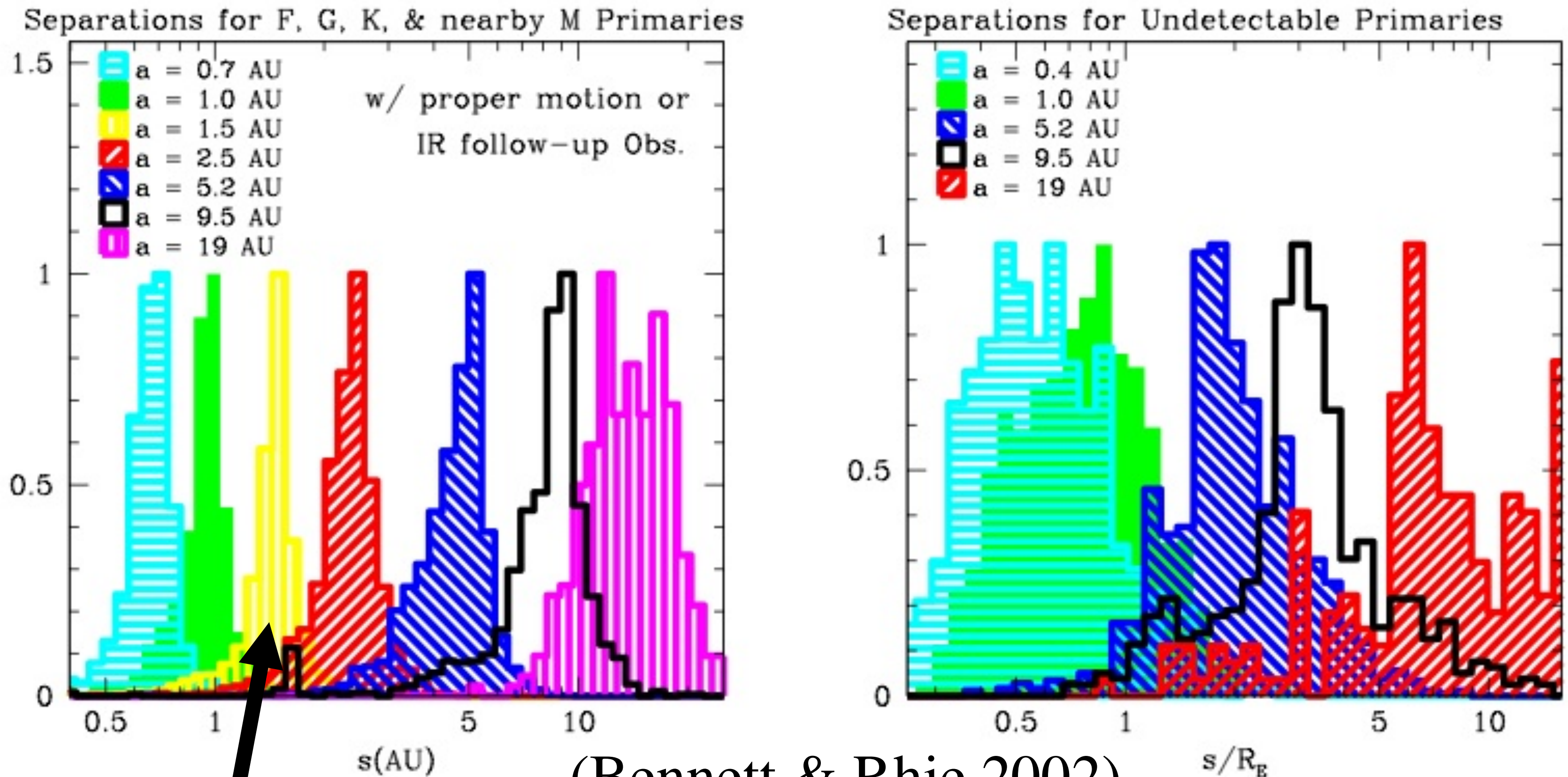
(Park et al. 2006)

What do we measure?

- For nearly all events*:
  - mass ratio
  - projected separation in Einstein ring radius.

  *Need to measure primary event properties.
- For most low-mass planet detections (and a large subset of higher-mass detections)
  - Einstein ring radius through finite source effects.
  - Gives a relationship between mass and distance of lens.
- Finally measure mass through a number of ways:
  - Isolate flux from the lens.
  - Measure microlens parallax (different relationship between mass and distance).

Projected Separations.



(Bennett & Rhie 2002)

Typical correction factor ~$(4/3)^{1/2}$

Do you learn *anything* from planet detections with no primary mass measurement?!?!

- ***You Betcha!***
- Exploring new regions of parameter space
  - *For example, a measurement of the frequency of ~10^{-7} mass ratio planets near the Einstein ring would be very interesting.*
  - *Or, measuring the frequency of ~10^{-5} mass ratio planets at ~10 Einstein radii.*
- *Furthermore, many of the host star mass measurements will be recoverable eventually (killer app for 30m telescopes with AO).*

Ground vs. Space

- Infrared.
  - More extincted fields $\Rightarrow$ higher event rates.
  - Smaller sources $\Rightarrow$ smaller planets, close-in planets.
- Resolution
  - Low-magnification events with main-sequence sources $\Rightarrow$ higher event rates, smaller planets.
  - Isolate light from the lens star $\Rightarrow$ Host mass characterization for the majority of events.
- Coverage
  - Complete coverage $\Rightarrow$ Better characterization
- Smaller systematics
  - Better characterization of parameters, more robust quantification of efficiencies.

Science: sub-Earth mass planets, habitable planets, free-floating planets, mass measurements.

What is the science?

- Understanding Planet Formation (hard!)
  - Must understand the physical processes by which μm sized grains grow by $10^{\sim 13\text{-}14}$ in size and $10^{\sim 38\text{-}41}$ in mass.
  - The various physical processes are imprinted on the distribution functions of mass, semimajor axis, as a function of host star mass.
  - The plan: *measure these distribution functions as accurately as possible over as broad a range of planet and host properties as possible!* (Measure the demographics of exoplanets.)
  - *Kepler* : $a<2$ AU, $M>M_{Earth}$; *WFIRST*: the rest.
- Habitable Planets
  - Measure the frequency of potentially habitable planets.
  - Must understand *habitability*.

Specific Questions:

Abundances of planets:

- How does the frequency of planets depend on location in the Galaxy?
- Is planet ejection a common by-product of planet formation and evolution?
- ***How do planet frequencies depend on primary mass?***
- ***How common are Mars-mass planets?***

Architectures of Planetary Systems:

- Do most giant planets migrate? Or stay close to their supposed birth sites?
- What is the frequency of solar system analogs?
- Is the distribution of planet masses beyond the snow line different from close-in planets? (or, how does migration sort planets?)
- What are the architectures of multi-planet systems beyond the the snow line?
- ***Are there features and/or breaks in the mass function of planets beyond the snow line?***

Habitable Planets and Habitability

- ***What is the frequency of solar system analogs?***
- ***What are the frequencies of potentially habitable planets?***
- ***What are the frequencies of massive moons?***

Quantitative Science Goals.

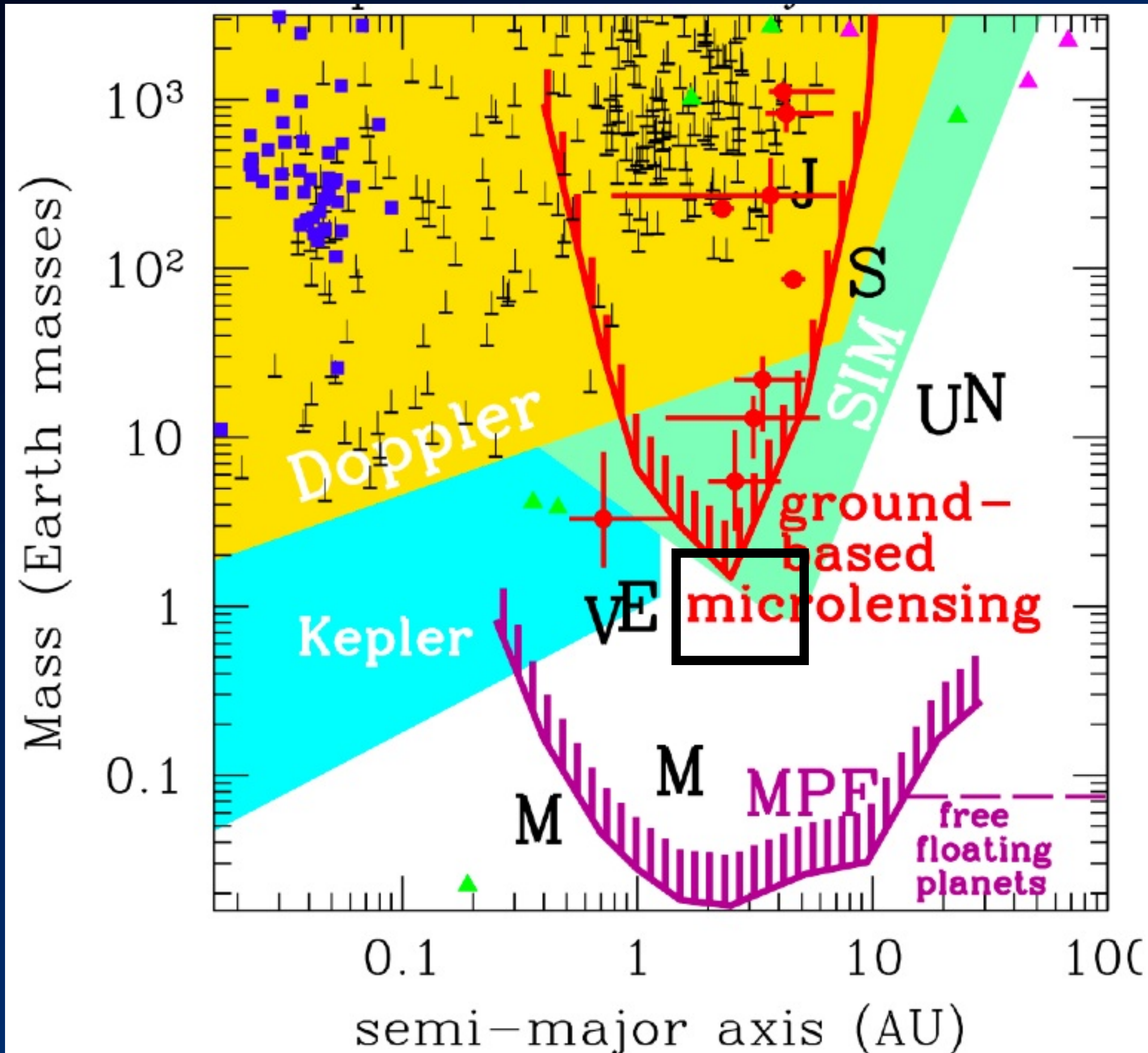
- (SG1) Determine the mass ratio, and projected separation probability distribution (in units of the Einstein ring radius) for cold planets with $M>M_{Earth}$ and $a>0.5$ AU to a precision TBD.
- (SG2) Measure the frequency of potentially habitable planets to a precision TBD.
- (SG3) Measure the frequency of free-floating planets with $M> M_{Earth}$ to a precision TBD.
- (SG4) Measure the host star masses of XX% of the detections in order to determine the mass and projected separation distributions in physical units.

Defining a FOM.

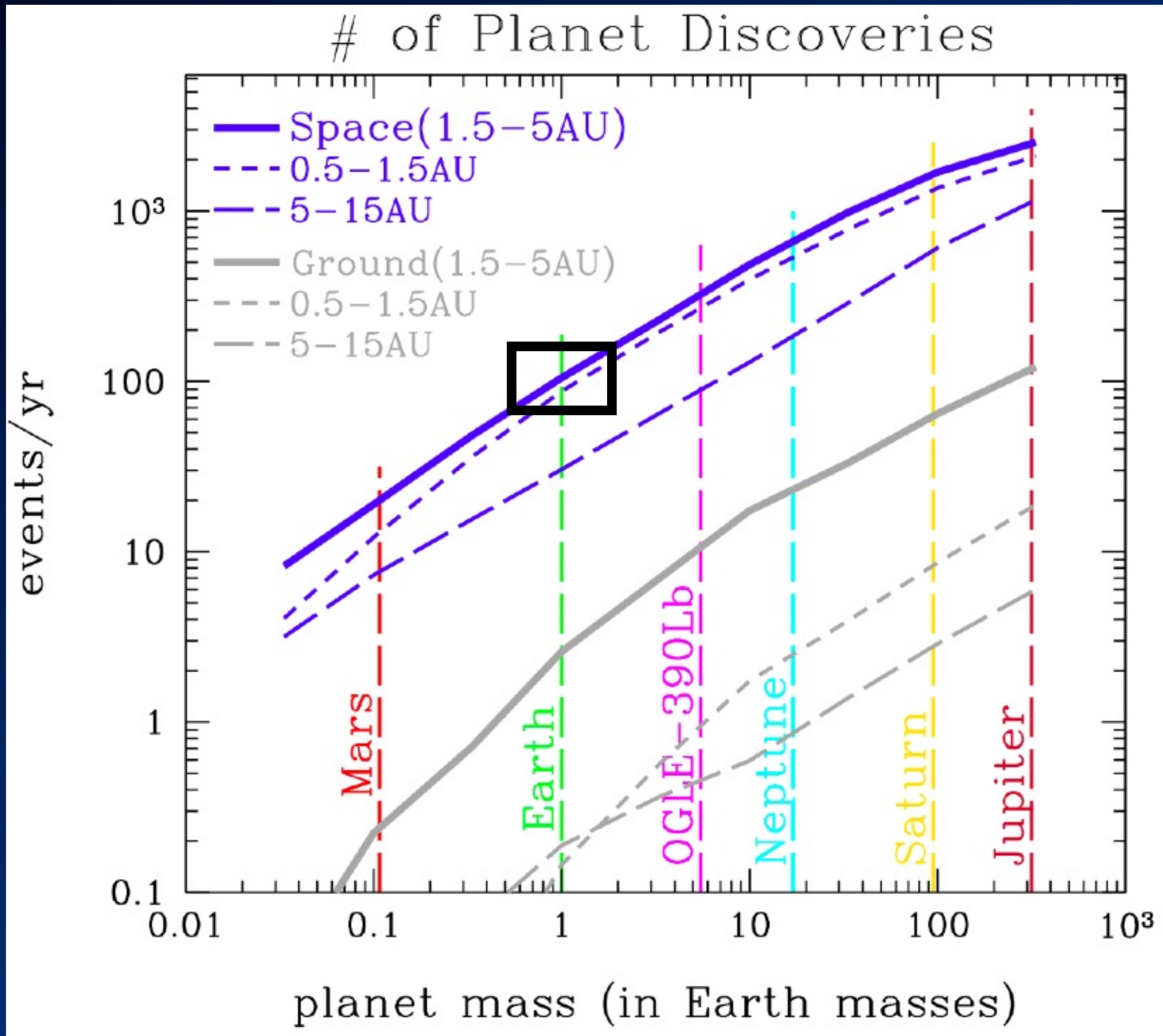
- Difficulty: collapse the entire N-dimensional parameter space of the properties of the detected planets to one number.
- Considerations:
  - Should not encompass a large range of detection sensitivities.
  - Should be focused on the region of interest and novel capabilities.
  - Should not straddle any detection thresholds for reasonable mission designs.
  - Should be directly relatable to, and hopefully scale simply with, the other mission products.
  - Should be directly related to the mission properties (if possible) and hopefully amenable to analytic insight.

Primary Figure of Merit

- **(FOM1) Number of planets detected (at $\Delta\chi^2$=160) with 0.5-2M_{Earth} and 1.25-5 AU, assuming every main-sequence star has one planet logarithmically distributed throughout this range.**
- For a 4 × 9 month MPF mission, this FOM~400. (Note MPF is 1.1m, ~0.65 sq. deg, 0.25" pixels).
- Consistent with RV, Microlensing extrapolations (Sumi et al. 2010, Howard et al. 2010)
- (if 20% of MS have such planets, we will detect ~80 planets and will measure this frequency to ~10%.)



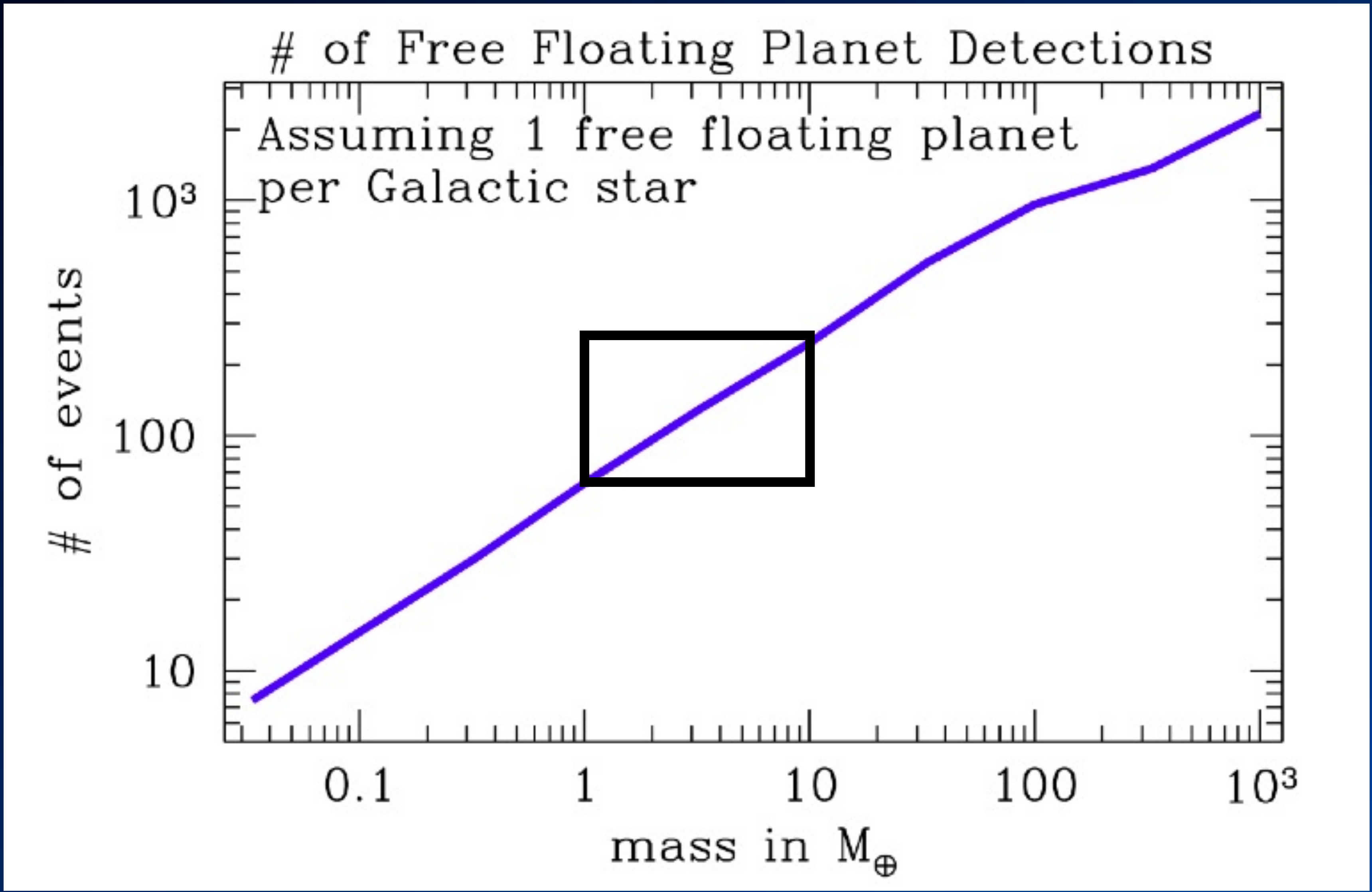
Mass (Earth masses)
semi−major axis (AU)
Doppler
Kepler
SIM
ground−based microlensing
MPF
free floating planets
J
S
U
N
V
E
M
M



# of Planet Discoveries
Space(1.5−5AU)
0.5−1.5AU
5−15AU
Ground(1.5−5AU)
0.5−1.5AU
5−15AU
events/yr
0.1
1
10
100
10³
0.01
0.1
1
10
100
10³
planet mass (in Earth masses)
Mars
Earth
OGLE-390Lb
Neptune
Saturn
Jupiter

Secondary FOM

- (FOM2) The number of habitable planets detected assuming every MS star has one, where habitable means 0.5-2M_{Earth}, and [0.8-1.7 AU]$(L/L_{sun})^{1/2}$
- (FOM3) The number of free-floating 1-10 M_{Earth} planets detected, assuming one free floating planet per star.
- (FOM4) The fraction of the planets detected in FOM1 for which masses can be measure to 20% (for MPF, this fraction was more than half).



For MPF, FOM3~120

TABLE 2

TERRESTRIAL PLANET DETECTION SENSITIVITY FOR $\epsilon = 10^{-5}$ AT 0.7–1.5 AU

ϵ	FOV (deg^2)	MINIMUM ERROR	FWHM	EFFECTIVE TELESCOPE APERTURE (m) 1.0	1.25*	1.6	2.0
10^{-5}	1.5	0.3	0.32	0.680	0.793	0.906	1.016
10^{-5}	2.0	0.3	0.32	0.803	0.937	1.074	1.202
10^{-5}	2.5	0.3	0.32	0.925	1.082	1.243	1.389
10^{-5}	1.5	0.15	0.32	0.709	0.834	0.974	1.114
10^{-5}	2.0	0.15	0.32	0.837	0.985	1.153	1.320
10^{-5}	2.5	0.15	0.32	0.965	1.136	1.322	1.526
10^{-5}	1.5	0.3	0.24	0.732	0.846	0.969	1.095
10^{-5}	2.0*	0.3*	0.24*	0.863	1.000*	1.148	1.296
10^{-5}	2.5	0.3	0.24	0.994	1.154	1.326	1.497
10^{-6}	1.5	0.15	0.24	0.758	0.885	1.034	1.190
10^{-5}	2.0	0.15	0.24	0.894	1.046	1.225	1.411
10^{-5}	2.5	0.15	0.24	1.031	1.207	1.415	1.632
10^{-5}	1.5	0.3	0.16	0.769	0.889	1.039	1.164
10^{-5}	2.0	0.3	0.16	0.906	1.049	1.230	1.372
10^{-5}	2.5	0.3	0.16	1.042	1.209	1.421	1.582
10^{-5}	1.5	0.15	0.16	0.794	0.928	1.101	1.256
10^{-5}	2.0	0.15	0.16	0.936	1.094	1.302	1.483
10^{-5}	2.5	0.15	0.16	1.078	1.261	1.504	1.712

NOTE.—This table shows the ratio of the number of terrestrial planet detections as a function of the telescope aperture, field of view (FOV), and effective point-spread function FWHM. The parameters of the *GEST* MIDEX proposal are indicated with asterisks.

(Bennett & Rhie 2002)

To Do.

- Agree on primary and secondary FOM.
- Determine how the FOM vary as a function of the mission parameters.
  - FOV, Aperture, Pixel Size, Total Observing Time.
- Given a FOM, determine the accuracy with which one can measure the planet distribution functions and achieve the science goals.
- Define a baseline mission.